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A SOFTWARE PACKAGE FOR ESTIMATING TIME DIFFERENCES FOR ARTILLERY SOUND RANGING APPLICATIONS

NOVEMBER 1979

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The Fortran program entitled "Time Differences Estimator Program" is presented and documented. The program will accept a given number of microphone signals each containing a specified number of data points from a fixed data format and determine the time differences between signal bursts that appear within the record length. It also gives a measure of reliability to associate with the time differences and provides, through a least square error procedure, a consistent set of relative times that can be used as input data to a position

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20. ABSTRACT (cont)

estimator. Results from using the program on a number of recorded signals from C4 explosions approximately 12 km away are presented showing target location errors of approximately 200 meters.

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I would like to thank Bernard Engebos and Walter Miller of the U. S. Army Atmospheric Sciences Lab for their excellent assistance during the tenure of the contract. The work was supported through the Scientific Services Program, Battelle Columbus Laboratories under Contract DAAG29-76-D-0100, Delivery Order No. 1205.

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I. INTRODUCTION

The main problem of sound ranging is to determine the location of a transient sound source by examining the signals received at an array of microphones. The problem can be logically broken down into two main parts. First the determination of the relative arrival times of the sound at the microphones and second, the use of this information to estimate the position. In this paper we concentrate on the determination of relative arrival times.

In the past, the arrival times at each microphone were determined by visually selecting a point of charge, the so-called "break point", from strip chart recorded signals [1]. Some methods used to determine these break points have been: first inflection, first maximum after inflection and first cross over after inflection. A comparative study of these methods is given in Dean [2]. In contrast to the break point methods, the author [3] proposed a procedure to obtain more accurate timing information from the received microphone signals by using the correlation between signals. The method when implemented on a digital computer would not only speed up the determination of the relative arrival times but provide more accurate results with less chance for reading errors than the visual techniques.

The purpose of this paper is to document a Fortran realization of the correlation technique described in [3] and present results from using field data from the PASS [4] experiment as input. These limited results indicate that, under a controlled experimental environment, the overall method provides reasonably good time differences estimates which, when used with the proper meteorological data, give good position estimates.

II. GENERAL DESCRIPTION OF TIME DIFFERENCES ESTIMATOR PROGRAM

The overall structure of the computer program for determining the relative time differences consists of the following basic sections: (A) Initialization and acceptance of input data, (B) a determination of the time windows that would enclose the signal received from the source and a calculation of the energies within the windows, (C) a prefiltering operation that would overcome wind and extraneous noise, (D) a pair by pair correlation to determine a rough time difference and a measure of correlation, (E) the determination of an overall least square time fit, and (F) an outputting of results. A general flow chart indicating processing structure is given in Figure 1, the program listing is given in Appendix A, and each main block is described in detail in the following sections. Each of the subheadings under the main blocks are set apart by comment cards in the program for ease in presentation.

A. Initialization and Acceptance of Data

1. Initializing. In the initialization portion of the program there are a number of parameters that must be specified and dimensioned. The main parameters are:

NMIC = Number of microphones

NL = Number of data points for each microphone

NSW = Number of points in the sliding window

NPFW = number of points in the Fourier window

The number of points in the sliding window is chosen to be approximately the number of points in the expected signal. By examining the C4 data from the PASS experiment, an example of which appears in Appendix C, it was seen that signals were in the 300-375 msec length and at a sample rate of 1 K samples/second this means approximately 350 samples. The number of points in the Fourier window was selected to be 1.5 times the number in the sliding

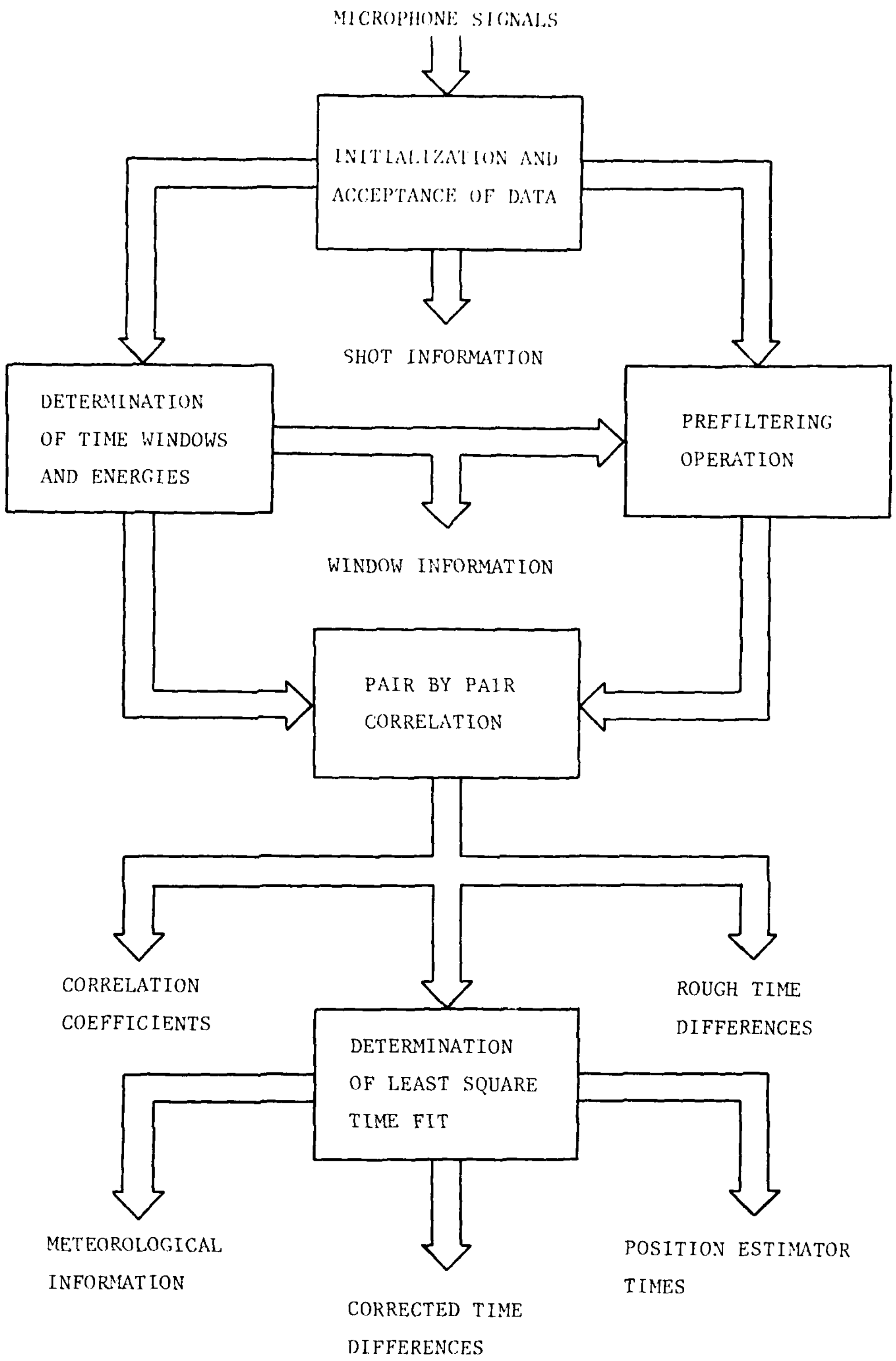

Figure 1. Processing structure of the Time Differences Estimator Program

window to make sure that most of the signal was within the window. For the C4 this meant approximately 500, and since the Fourier transform can be obtained faster for powers of 2 by the FFT, NPFW was selected to be 512 and NWS = 342. The data files provided by personnel from the Physical Sciences Laboratory (PSL), Las Cruces, New Mexico, were constructed to be 1920 samples per signal in length; therefore, NL is set equal to 1920. The following dimension and complex cards would then be required:

```
DIMENSION IDAY(NMIC), IHOUR(NMIC), IMIN(NMIC), SEC(NMIC), MIC(NMIC), TIME(NMIC)

DIMENSION TAU(NMIC,NMIC), IT(NMIC), NR(NMIC), E(NMIC), RTAU(NMIC,NMIC),
  CTAU(NMIC,NMIC), GAM(NMIC,NMIC)

DIMENSION SMIC(NMIC,NL,LRST(NMIC, G(NMIC,NMIC), AT(NMIC), A(NMIC,NMIC),
  JC(NMIC-1), V(2)

DIMENSION CMEAS(NMIC), MCOM(11).

CMPLEX X(2·NPFW), Y(2·NPFW), WORK(2·NPFW), XX(2·NPFW), YY(2·NPFW), ZZ(2·NPFW)
```

2. Data file Format. The input to the program was data taken from the PASS Experiment that had been transferred to files in the UNIVAC 1108 system by PSL personnel. The format modified slightly to include MET data and file identification for these data files is illustrated in Figure 2. Each data file is 728 lines in length with the first eight lines containing timing and shot information while the remaining lines contain the data for each microphone. To be more specific in the format we have the following line by line structure.

```
            I2    I2    I3    I2   I2      F6.3      F4.1    I4    I2
Line 1:  _ _ 6 _ _ 1 _ 341 _ 12 _ 36 _ _ 2.024 _ _ _ 06.7 _ 6380 _ 09
             a     b     c     d    e        f         g      h     i
```

a = Number of microphones

b = PASS source number

c = Day of Pass shot

d = Hour of Pass shot

e = Min of Pass shot

```
6  1 341 12 36  2.024     6.7 6380  9
6  SOURCE 1 MINE ARRAY B      FILE(51-B341-MB-1.)
1  1920  120 27 341 12 36 35.611                                          HEADER
2  1920  120 28 341 12 36 36.507
3  1920  120 29 341 12 36 37.787
4  1920  120 30 341 12 36 39.451
5  1920  120 31 341 12 36 41.499
6  1920  120 32 341 12 36 43.803
 12   14   15   14   11   10   11   11    9    8    9   12   12   12   13   15
 15   16   17   14   13   11   10   11   11   10   10   11   15   15   15   16
 14   15   16   16   14   13   12   10    9    8   10   10   12   14   13   14
  .    .                                                                    .  MIC(27)
  .    .                                                                    .
  .    .                                                                    .
  8   10    9    7    6    6    7    5    5    2    2    3    6    4    4    6
  6    7    9    8    6    6    7    7    6    3    1    1    3    3    2    2
  6    7    8    9    8    8   10   11    8    6    5    5    6    6    7    8
  9   10    9   12   13   12   10   11   10    9   10    8    7    8    7    6
  6    9   12   14   13   13   11   12   13   13   11   10    7    6    6    7
  .    .                                                                    .  MIC(28)
  .    .                                                                    .
  .    .                                                                    .
  0    0    1    2    3    2    1    3    2    2    2    4    4    3    1   -1
 -2   -1   -2   -1    0    3    2    3    3    4    4    4    4    2    1    0
 -1    0    0   -1    0    2    3    4    6    7    4    3    5    5    4    3
  3    3    3    4    3    4    6    6    7    8    8    8    8    9    8    6
  5    3    3    4    4    5    6    8   10   10    9    8    9    8    7    7
  .    .                                                                    .  MIC(29)
  .    .                                                                    .
  .    .                                                                    .
  4    3    3    0    1    0    1   -1   -1    2    3    2    2    2    4    4
  3    1    0    0   -1    0   -1   -1    0    2    3    2    2    3    4    4
  4    4    3    1    2    2    2    1    1    1    4    5    6    8    8    7
  8   10    9    5    3    3    5    6    4    3    5    7    8    9   10   11
 10    9    7    8   10   10    8    7    7    6    7    8   11   11   13   14
  .    .                                                                    .  MIC(30)
  .    .                                                                    .
  .    .                                                                    .
  6    5    5    6    6    7    4    3    2    2    3    5    3    3    4    5
  4    6    7    7    6    7    6    6    4    0    2    1    2    4    6    6
  7    9   10   11   10   10   11   10    8    5    3    4    6    6    5    6
  8    9   12   13   13   13   14   14   13   11   11    9   10    9    9   10
 12   12   12   15   16   17   18   17   17   15   14   13   14   15   14   14
  .    .                                                                    .  MIC(31)
  .    .                                                                    .
  .    .                                                                    .
-11  -15  -17  -18  -20  -22  -24  -27  -28  -28  -28  -32  -33  -39  -38  -37
-37  -35  -35  -32  -28  -26  -23  -20  -18  -15  -12   -9   -7   -4   -1    2
  7   10   13   18   22   24   27   30   32   35   35   36   35   36   36   35
 34   31   29   29   31   31   29   27   24   20   18   16   17   13    7    2
  1   -1   -1   -4   -5   -5   -7   -6   -3   -2   -4   -5   -5   -3   -4   -4
  .    .                                                                    .  MIC(32)
  .    .                                                                    .
  .    .                                                                    .
  7    4    3    4    3    3    1    2    6    4    4    5    4    5    7    7
  6    7    4    2    2    3    3    1    4    5    5    7    8    8    8    8
```

Figure 2. Illustration of Data File Format

f = Second of Pass shot

g = Effective temperature in Deg C. for shot

h = Wind direction in MILS

i = Wind speed in KNOTS

$$\text{Line 2: } \_\_\underbrace{\overbrace{6}^{I2}}_{a}\_\_ \underbrace{\text{SOURCE 1 MIKE ARRAY B}}_{b}\_\_\_\_\_ \text{FILE (S1-D341-MB-1.)}$$

a = Number of microphones

b = Indication of source position, microphone array and file identification

$$\text{Lines 3-8: } \_\_\underbrace{\overbrace{1}^{I2}}_{a}\_\_\underbrace{\overbrace{1920}^{I4}}_{b}\_\_\underbrace{\overbrace{120}^{I3}}_{c}\_\underbrace{\overbrace{27}^{I2}}_{d}\_\underbrace{\overbrace{341}^{I3}}_{e}\_\underbrace{\overbrace{12}^{I2}}_{f}\_\underbrace{\overbrace{36}^{I2}}_{g}\_\underbrace{\overbrace{35.611}^{F6.3}}_{h}$$

a = Microphone index J

b = Number of values per microphone in record

c = Number of lines of data for each microphone

d = PASS microphone number: MIC(J)

e = Starting day of microphone record

f = Starting hour of microphone record

g = Starting min of microphone record

h = Starting second of microphone record

$$\text{Line 9: } \underbrace{\overbrace{\_\_\_ 12}^{F5.0}}_{a_1}\ \underbrace{\overbrace{\_\_\_ 14}^{F5.0}}_{a_i} \cdots \underbrace{\overbrace{\_\_\_ 15}^{F5.0}}_{a_{16}}$$

a_i = value of microphone 1 at time i = 1,..., 16

Line 10: a_i = value of microphone 1 at time i = 17,..., 32

⋮

Line 128: a_i = value of microphone 1 at time i = 1905,..., 1920

In a similar fashion

Lines 129-248: values of microphone 2 at times i = 1, 2,..., 1920

249-368: values of microphone 3 at times i = 1, 2,..., 1920

369-488: values of microphone 4 at times i = 1, 2,..., 1920

489-608: values of microphone 5 at times i = 1, 2,..., 1920

609-728: values of microphone 6 at times i = 1, 2,..., 1920

3. Bringing in Data from Master File. In the original version of the program a subroutine was provided by PSL to read the data files and transfer this information to the SMIC(J,I) indexed array. In the present version the new subroutine RDATA(SMIC,MIC,IDAY,IHOUR,IMIN,SEC,TEMP,MILS,KNOTS) was written to obtain a desired output format and include meteorological and other cataloging information. A Fortran listing of the subroutine appears in Appendix B. To bring in the data to the program arrays simply requires the Fortran statement:

```
______ CALL RDATA(SMIC,MIC,IDAY,IHOUR,IMIN,SEC,TEMP,MILS,KNOTS)
```

The indexed arrays: SMIC, MIC, IDAY, IHOUR, IMIN, SEC are described in the previous section and represent the values and starting time information for each microphone signal, while the TEMP, MILS, and KNOTS are defined below.

TEMP = Effective temperature at the time of the shot in degrees Centigrade

MILS = The angle of wind in mils at the time of the shot

KNOTS = The speed of the wind at the time of the shot

B. Determination of Time Windows and Energies

In many cases the time intervals of the received signals are much larger than the transient signal searched for and if the correlation procedure is used on the entire length of each signal an exorbitant amount of time would be consumed. Therefore, windows are established around the location of the signal bursts. This part of the procedure consists of computing rough arrival times, starting points for windows and the energies within the windows.

1. Computation of Rough Arrival Times. The rough arrival times are determined by the use of an energy detector for each signal. That is the energy within a sliding time window (I, I+NSW) is calculated for all values of time I equal 1 to NL-NSW. The point in time I_{MAX} for the Jth microphone signal where the energy is maximum is called the rough starting time LRST(J). If X(J,I) I = 1,2,...,NL is the input to the energy detector for the Jth signal, the running value of the energy within the Jth sliding window becomes

$$E(J,I) = \sum_{k=I}^{I+NSW} SMIC^2(J,k) \qquad I = 1,2,\ldots,NL-NSW$$

LRST(J) = value of I such that E(J,I) is maximized.

2. Computation of Fourier Window Starting Points. The starting point NR(J) for the Jth signal Fourier window is selected by bracketing the rough starting time on both sides by NSW/4. Care must be taken to make sure that the beginning and ending points of the window remain within 1 and NL. This is done by making the following assignment for NR(J).

$$NR(J) = \begin{cases} 1 & \text{if } LRST(J) - NSW/4 \leq 1 \\ LRST(J) - NSW/4 & \text{if } 1 < (LRST(J)-NSW/4) \leq NL - 3NSW/2 \\ NL-3\cdot NSW/2 & \text{if } (LRST(J)-NSW/4) > NL - 3NSW/2 \end{cases}$$

3. Computation of Signal Energy within the Fourier Window. Once NR(J) has been determined the energy within each Fourier window can be calculated as follows:

$$E(J) = \sum_{k=NR(J)}^{NR(J)+3NSW/2} SMIC^2(J,k)$$

The starting point of the Fourier window and signal energy are then printed out for each microphone.

C. <u>Prefiltering Operation</u>

In many cases there is noise present on the lines during the duration of the signals. The noise could come from a wide variety of sources including

wind noise, sixty cycle interference, and machine related noise. To characterize all these noises analytically becomes almost impossible. The program was designed, however, to try to minimize the effects these noises would have by prefiltering the data. This was done by using estimates of the spectrum of the noise, and the spectrum of the signal plus noise.

1. Determination of Starting Point for Noise Window. The noise window for each signal, selected to be before the Fourier window which contains the signal plus noise, consists of 512 points consistent with the Fourier window in size. By keeping the windows the same size the determination of the prefilter and application of the prefilter is simplified. The starting point for the noise window for each signal was determined by

$$\text{Start Point } (J) = NR(J) - 512$$

If this was less than zero for some J then the starting point for the Jth noise window was set equal to the first data point of that signal record. Since most of the data records had over 500 samples, i.e. 500 msec worth of noise preceding the signal, few cases of signal and noise window overlaps were reported.

2. Determination of Estimate of Noise Spectrum. For each pair of signals SMIC(I,L) and SMIC(J,L), and respective noise window starting points KXX and KYY, a rough estimate of the noise spectrum is desired. The estimation procedure used was that of obtaining the spectrum for each signal and simply averaging the results. To provide a spectrum compatible in samples the FOURG SUBROUTINE was used on each of the following signal vectors.

$$XX = [\overbrace{SMIC(I,KXX),\ SMIC(I,KXX+1),\ldots,\ SMIC(I,KXX+511)}^{\text{512 samples}},\ \overbrace{0,\ 0,\ldots,\ 0}^{\text{512 samples}}]$$

$$YY = [SMIC(J,KYY),\ SMIC(J,KYY+1),\ldots,\ SMIC(J,KYY+511),\ 0,\ 0,\ldots,\ 0]$$

The addition of zeros will not alter the spectrum determined and provide the proper frequency indices. The spectrum was then estimated by

$$\text{Spectrum for noise} = \frac{\text{FOURG(XX)} \cdot \text{FOURG*(XX)} + \text{FOURG(YY)} \cdot \text{FOURG*(YY)}}{2}$$

The noise spectrum was stored back in the real part of the complex array YY(L), L = 1,2,..., 1024.

3. Determination of Estimate of Signal Plus Noise Spectrum. For each pair of signals SMIC(I,L) and SMIC(J,L) and respective Fourier window starting points NR(I) and NR(J) the following signal vectors were defined.

$$XX = [\underbrace{\text{SMIC(I,NR(I)), SMIC(I,NR(I)+1),..., SMIC(I,NR(I)+511)}}_{\text{512 samples}}, \underbrace{0, 0,..., 0}_{\text{512 samples}}]$$

$$ZZ = [\text{SMIC(J,NR(J)), SMIC(J,NR(J)+1),..., SMIC(J,NR(J)+511)}, 0, 0,..., 0]$$

The signal plus noise spectrum was stored back in the real part of complex array XX(L), L = 1,2,..., 1024.

4. Computation of Prefilter Values. The prefilter that is to be applied to each pair of signals was selected to be of the form

$$H(L) = \phi_{ss}(L)/(\Phi_{ss}(L) + \Phi_{nn}(L)) \qquad L = 1,2,..., 1024$$

where $\phi_{ss}(L)$ and $\phi_{nn}(L)$ represent the value of the energy spectrum density of signal and noise respectively at index L. Since the $\phi_{ss}(L)$ was not known the prefilter frequency response was written in the following equivalent form

$$H(L) = 1 - \phi_{nn}(L)/(\Phi_{ss}(L) + \Phi_{nn}(L))$$

Since only the estimates of $\Phi_{nn}(L)$ and $\Phi_{ss}(L) + \Phi_{nn}(L)$ are available, care must be taken to insure that H(L) does not go negative. The program uses Real (XX(L)) and Real (YY(L)) to represent $\phi_{ss}(L) + \Phi_{nn}(L)$ and $\Phi_{nn}(L)$ respectively and defines PRC and PRD as

PRC = REAL(YY(L))/REAL(XX(L))

PRD = REAL(XX(L))

The prefilter value ZZ(L) at frequency index L is described as follows for L = 1,2,..., 1024.

$$ZZ(L) = \begin{cases} (0,0) & \text{If PRC} > 1 \\ (1,1) & \text{If PRD} < .001 \\ \text{CMPLX(H(L),H(L))} & \text{otherwise} \end{cases}$$

5. Application of Prefilter. Once the prefilter values have been determined and the product of the DFT of each positioned signal is eventually put in Y(L) L = 1,2,...,1024 the prefiltering operation is done simply by multiplying each frequency component by ZZ(L) that is

ZZ(L) = CMPLX (PREF,PREF)

Y(L) = Y(L)*ZZ(L)

6. Application of Comb Filter for 60 HZ and Harmonics

The power spectral density was obtained for microphone noise signals from the PASS experiment showing dc power, power in 60 HZ and harmonics, some low frequency wind noise, and some unidentified interference of approximately 7.8 HZ and higher harmonics. An example appears in Appendix C. To minimize the effects of these interferences a comb filter including a low pass filter was applied in the frequency domain. For the 1024 point Fourier transform the frequency indexes and corresponding analog and digital frequencies are given by:

index	digital frequency	corresponding analog frequency
k	$(k-1)\cdot 2\pi/1024$ radians	$(k-1)\cdot 2\pi/1024T$ radian/sec

Since the time T between samples is 1 msec for the PASS data the corresponding analog frequencies are spaced $2\pi/1.024$ rad/sec or .97656 HZ apart. The D.C. component index is one. Since 60 HZ and harmonics do not fall exactly on index numbers this causes a leakage to a band of frequencies that must be considered. The apparent index given in Table 1 is determined by:

Apparent index = freq.(1.024) + 1.

The upper index band required because of symmetry of the DFT is determined by

$$k_u = 2*NPFW + 2 - k = 1026 - k$$

TABLE 1 Comb Filter Frequency Bands

Identification	Frequency Band	Apparent Index	Lower Index Band k	Upper Index Band k_u
a	D.C.	1	1	1
b	0^+-7.8 HZ	1-8.9	2-10	1016-1024
c	60 HZ	62.44	60-65	961-966
d	120 HZ	123.88	121-126	900-905
e	180 HZ	185.32	183-188	838-843
f	140 HZ	246.76	244-249	777-782

The index information for the comb filter was given in the following data card

$$\text{\_ \_ \_ \_ \_ \_ DATA MCOMB/}\underbrace{1,}_{a}\ \underbrace{2,\ 10,}_{b}\ \underbrace{60,\ 65,}_{c}\ \underbrace{122,\ 126,}_{d}\ \underbrace{183,\ 188,}_{e}\ \underbrace{244,\ 249}_{f}/$$

The comb filter was applied by setting the values corresponding to the index bands equal to zero in the frequency domain output of the pair by pair correlation.

D. Pair by Pair Correlation

The pair by pair cross correlation $R_{xy}(L)$ of the windowed signals is accomplished in the frequency domain by use of the FFT algorithm. That is

$$R_{xy}(L) = \text{IDFT}[\text{DFT}(X(L))\cdot\text{DFT}^*(Y(L))]$$

Since the above operation performs circular correlation it is necessary to position the data signals X(L) and Y(L) such that the circular and linear correlation are the same. The * means complex conjugate and is needed to provide correlation rather than convolution.

1. Positioning of Signals for Determining the Cross Correlation. To obtain linear convolution resulting in proper correlation, the signals SMIC(I,L)

and SMIC(J,L) L = 1,2,...,512 are positioned as follows

L	1 ··	2	···	512	513	514	···	1024
Real X(L)	SMIC(I,1),	SMIC(I,2),	...,	SMIC(I,512),	0	0	···	0
Imag X(L)	0	0	...	0	0	0	···	0
Real Y(L)	0	0	...	0	SMIC(J,1),	SMIC(J,2),	...,	SMIC(J,512)
Imag Y(L)	0	0	...	0	0	0	···	0

2. Finding the Raw Time Differences between Windowed Signals. Once the DFT(X(L))·DFT*(Y(L)) is prefiltered and comb filtered the cross correlation $R_{xy}(L)$ is obtained back in the real part of array Y(L) L=1,2,...,1024 by taking the Inverse Fourier Transform. The Fortran statement uses a +1 to indicate inverse as follows.

```
______ CALL FOURG(Y,1024,+1, WORK)
```

A search is then performed on |Real(Y(L))|, L=1,2,...,1024 to obtain the maximum value CMAX of the cross correlation and the time TMAX of the maximum value. Because of the positioning of the signals the raw time difference is then given by

```
TAU(I,J) = TMAX - NPFW - 1
```

3. Determination of the Normalized Correlation Coefficient. The normalized correlation coefficient GAM(I,J) is obtained by dividing the maximum value by the square root of the product of the energies and is given by

```
GAM(I,J) = CMAX/((E(J)*E(I)) **0.5)
```

If the signals [SMIC(I,L)] and [SMIC(J,L)] are identical in shape but of different amplitudes the GAM(I,J) will be equal to 1. If there shapes are significantly different the value of GAM(I,J) will be approximately zero. In this way the normalized correlation coefficient provides a measure of similarity of the two signals tested.

4. Determination of the Rough Time Differences between Signals I and L. The raw time difference represents the time difference between the signals in the windows. To obtain the rough time differences between microphone signals

the raw time difference TAU(I,L) must be adjusted by the starting times of the windows as follows

$$RTAU(I,L) = FLOAT[IT(I)-IT(L)] + TAU(I,L)$$

These rough time differences TAU(I,L) I=1,2,...,NMIC, and L=I,I+1,...,NMIC are part of the input to the least square adjustment section.

E. Determination of Least Square Time Fit

The rough time difference RTAU(I,J) and normalized correlation coefficient GAM(I,J) I=1,2,...,NMIC J=1,2,...,NMIC are now used to obtain a consistent set of time differences by using a weighted least squares procedure. Each step in the procedure is described in the following paragraphs.

1. Establishment of Weights for Least Square Time Fit. A weight is attached to each one of the rough time differences indicating a measure of reliability of those estimates. The measure or weight G(I,J) assigned to RTAU(I,J) is defined to be a function of the normalized correlation coefficient GAM(I,J). Different functional relationships have been played with, but at present no way of favoring one over the others has been established. The program in the present form uses the following weighting.

$$\begin{aligned} G(I,J) &= (GAM(I,J))^2 && \text{if } GAM(I,J) < 0.5 \\ &= (GAM(I,J))^{1/2} && \text{if } GAM(I,J) > 0.5 \end{aligned}$$

This attaches slightly more influence to time difference values that have a normalized correlation coefficient greater than 0.5 over those that have correlations less than 0.5.

2. Determination of Least Square Time Fit with MIC 1 as a Reference. The weights G(I,J) described above are used to define a measure of performance e given by

$$e = \sum_{I>J}^{NMIC} \sum_{J=1}^{NMIC} G(I,J)\ (RTAU(I,J) - (TIME(I) - TIME(J)))^2$$

The objective is to find the times TIME(I) I=1,2,..., NMIC such that e is minimized. A solution of this problem for G(I,J)=1 is given by the Author [3] and requires solving for n microphone signals a set of simultaneous linear equations in n-1 unknowns when a given microphone has been selected as a reference. In Appendix C a solution for arbitrary G(I,J) with MIC1 as a reference is presented resulting in the following set of simultaneous equations in t_i where t_i is the relative time of arrival of the ith signal.

$$\begin{bmatrix} \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} = - \begin{bmatrix} G(1,1) & G(2,3) & G(2,4) & G(2,5) & G(2,6) \\ G(2,3) & G(2,2) & G(3,4) & G(3,5) & G(3,6) \\ G(2,4) & G(3,4) & G(3,3) & G(4,5) & G(4,6) \\ G(2,5) & G(3,5) & G(4,5) & G(4,4) & G(5,6) \\ G(2,6) & G(3,6) & G(4,6) & G(5,6) & G(6,6) \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \end{bmatrix}$$

where

G(1,1)=-(G(1,2)+G(2,3)+G(2,4)+G(2,5)+G(2,6))

G(2,2)=-(G(1,3)+G(2,3)+G(3,4)+G(3,5)+G(3,6))

G(3,3)=-(G(1,4)+G(2,4)+G(3,4)+G(4,5)+G(4,6))

G(4,4)=-(G(1,5)+G(2,5)+G(3,5)+G(4,5)+G(5,6))

G(5,5)=-(G(1,6)+G(2,6)+G(3,6)+G(4,6)+G(5,6))

and

α_2 = - G(1,2)R(1,2)+G(2,3)R(2,3)+G(2,4)R(2,4)+G(2,5)R(2,5)+G(2,6)R(2,6)

α_3 = - G(1,3)R(1,3)-G(2,3)R(2,3)+G(3,4)R(3,4)+G(3,5)R(3,5)+G(3,6)R(3,6)

α_4 = - G(1,4)R(1,4)-G(2,4)R(2,4)-G(3,4)R(3,4)+G(4,5)R(4,5)+G(4,6)R(4,6)

α_5 = - G(1,5)R(1,5)-G(2,5)R(2,5)-G(3,5)R(3,5)-G(4,5)R(4,5)+G(5,6)R(5,6)

α_6 = - G(1,6)R(1,6)-G(2,6)R(2,6)-G(3,6)R(3,6)-G(4,6)R(4,6)-G(5,6)R(5,6)

with

R(I,J) = RTAU(I,J)

This set of equations was solved by using the GJR subroutine package from the 1108 Large Scale Systems Math Pack which is fully described in [5]. The subroutine is accessed with the following call

```
CALL GJR(A,6,5,5,6,$400,JC,V)
        a b c d e   f    g  h
```

where

a = augmented coefficient matrix

b = maximum number of columns in A

c = maximum number of rows in A

d = the number of rows in A

e = the number of columns in A

f = statement number control is returned if an overflow is detected

g = control array

h = on input V(1) is the option indicator, which to solve equations is 4, on output V(2) contains the value of the natural log of the absolute value of the determinant and V(1) contains the sign of the determinant

On output the last column of A is the solution vector $[t_2, t_3 \ldots t_6]$ and is called AT(2),AT(3),...,AT(6). Since microphone 1 was defined to be the reference, AT(1) is set equal to zero. The AT[I] represents the starting time for the signal in the Ith window relative to the signal in window 1.

3. Adjustment of Time Differences. Using the AT vector, a raw corrected time difference can be found by the difference of the components

$$TAU(I,J) = AT(I) - AT(J) \qquad I=1,2,\ldots,6 \qquad I< J\leq 6$$

The least square corrected time difference in milliseconds can then be formed by

$$CTAU(I,J) = TAU(I,J) + FLOAT[IT(I)-IT(J)]$$

4. Selection of MIC to be used as reference. To select a microphone as a reference for determining the relative times for the position estimator requires

a specification of a performance criterion. We would like to select the MIC as reference that gives the best possible relative times for the position estimator. Upon examining data, it was found that position estimates were sensitive to the selection of a MIC reference even though a least squares precedure had been performed on the time differences. No direct relationship was established however and the following procedure represents a reasonable way to select the reference with no sense of optimality implied. As the normalized correlation coefficient is a measure of reliability of the time differences determined, the sum of the correlation coefficients for all time differences associated with a particular microphone represents a measure of reliability of the time differences for that microphone. This measure was called CMEAS(I) I=1,2,...,6 and given by

$$\mathrm{CMEAS(I)} = \sum_{\substack{J=1 \\ J \neq I}}^{6} \mathrm{C(I,J)}$$

The value K for which CMEAS(K) K=1,2,...,6 is a maximum is called KMAX and represents the number of the microphone to be used as a reference. In the output of the times for the position estimator the reference microphone is identified by having the time 0.000.

5. Determination of Relative Times for the Position Estimator. The position estimator USRAN1[1] requires six relative arrival times and the proper meteorological data as input to determine the position of the source. The number (KMAX) of the microphone signal that was selected as a reference was determined previously. To find the times relative to this microphone could be easily accomplished by filling out the lower triangular part of the CTAU(I,L) array with the negative of upper triangular part. In this way the time differences with respect to each microphone appear on the rows of CTAU(I,L) and the selection of the KMAX microphone corresponds to selecting a row.

F. Printing the Output

An example of the overall program output format is given in Figure 3 and consists of the four basic parts described below.

1. Shot Information. The header information is in reference to the data files from the PASS experiment and gives the day, time, and position of the shot as well as the position number, starting times and lengths (MSEC) of the data record for the microphones recording.

2. Window Information. The window starting time in MSEC determined by the program relative to the starting times for each microphone record are given along with the signal energy within the window. The microphones numbered 1 through 6 correspond to the normal ordering of the PASS microphone numbers. The window signal energy and starting time could be used in an interactive mode (not programmed at this time) to allow the operator to check if a signal appears in the window or not.

3. Time Differences Information. The normalized correlation coefficient, time differences in MSEC, and corrected time differences in seconds are given for each pair of microphone signals. These results may be used to infer the overall reliability provided by the normalized correlation coefficient and a measure of consistency by examining the changes made in the rough time differences RTAU(I,J) to get the corrected time differences.

4. Met and Timing for Position Estimator. The times in seconds and the Met information that could be used as input to a position estimator are provided for interfacing purposes. The timing information appears in an array TIME(J) J=1,2,...,6 while the temperature, wind direction and wind speed are labeled TEMP, MILS, and KNOTS respectively.

III. USING THE PROGRAM

The procedure given in this section will apply to the use of the program on the WSMR UNIVAC 1108 system. Presently the program is stored under file

```
     DAY 341:  SHOT TIME  8:15 HRS   1.896 SEC
     SOURCE 2 FIRE ARRAY 6
     MICS: 27,28,29,30,31,32        1920 VALUES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

     MIC(27):  8:15 HRS  34.771 SEC        MIC(30):  8:15 HRS  36.379 SEC
     MIC(28):  8:15 HRS  34.971 SEC        MIC(31):  8:15 HRS  37.659 SEC
     MIC(29):  8:15 HRS  35.483 SEC        MIC(32):  8:15 HRS  39.451 SEC

THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

      MIC 1      MIC 2      MIC 3      MIC 4      MIC 5      MIC 6

       742        726        677        666        686        565

THE SIGNAL ENERGY WITHIN EACH WINDOW

       MIC 1          MIC 2          MIC 3          MIC 4          MIC 5          MIC 6

     1433159.        264966.       8322272.      21142428.      35415047.      34593879.

THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

       GAMMA(1,2)=  .678        RTAU(1,2)=     5.0        CTAU(1,2)=  .014
       GAMMA(1,3)=  .703        RTAU(1,3)= -422.0         CTAU(1,3)= -.436
       GAMMA(1,4)=  .669        RTAU(1,4)=-1324.0         CTAU(1,4)=-1.340
       GAMMA(1,5)=  .653        RTAU(1,5)=-2652.0         CTAU(1,5)=-2.642
       GAMMA(1,6)=  .755        RTAU(1,6)=-4329.0         CTAU(1,6)=-4.319
       GAMMA(2,3)=  .674        RTAU(2,3)= -455.0         CTAU(2,3)= -.451
       GAMMA(2,4)=  .703        RTAU(2,4)=-1359.0         CTAU(2,4)=-1.354
       GAMMA(2,5)=  .730        RTAU(2,5)=-2656.0         CTAU(2,5)=-2.656
       GAMMA(2,6)=  .753        RTAU(2,6)=-4333.0         CTAU(2,6)=-4.333
       GAMMA(3,4)=  .774        RTAU(3,4)= -903.0         CTAU(3,4)= -.903
       GAMMA(3,5)=  .756        RTAU(3,5)=-2201.0         CTAU(3,5)=-2.206
       GAMMA(3,6)=  .724        RTAU(3,6)=-3877.0         CTAU(3,6)=-3.882
       GAMMA(4,5)=  .795        RTAU(4,5)=-1298.0         CTAU(4,5)=-1.303
       GAMMA(4,6)=  .753        RTAU(4,6)=-2974.0         CTAU(4,6)=-2.979
       GAMMA(5,6)=  .784        RTAU(5,6)=-1676.0         CTAU(5,6)=-1.676

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

                          TIME(1)= -4.319 SEC
                          TIME(2)= -4.333 SEC
                          TIME(3)= -3.882 SEC
                          TIME(4)= -2.979 SEC
                          TIME(5)= -1.676 SEC
                          TIME(6)=   .000 SEC

THE MET TO BE USED AS INPUT TO POSITION ESTIMATOR

                              TEMP=  5.4 DEGS C.
                    WIND DIRECTION= 6180 MILS
                        WIND SPEED=    9 KNOTS
```

Figure 3.   Example of the program output format

name and element LCLPF.SOUNDR in both a symbolic and absolute form. The following control statements will execute the program;

@ASG, AZ S3-D341-MB-1.	Assign data file to run
@USE 12., S3-D341-MB-1	Use file S3-D341-MB-1 as logical unit 12
@XQT LCLPF.SOUNDR	Execute program.

If the program is to be executed on another computer a duplicate of the symbolic form of SOUNDR must be obtained and if a different data structure is to be used the subroutine RDATA must be rewritten. The main program and subroutine can then be compiled on the computer to be used.

IV. RESULTS

The program LCLPF.SOUNDR was run using various signals from the PASS experiment as input. The results for the test shots given in Table 2 are shown in Figures 4 through 10. The times and Met data indicated in Figures 4 through 10 were used in a position estimator program resulting in the Miss distances given in Table 3.

TABLE 2. PASS Data Shots Used in Program Testing

UNIVAC 1108 File No.	Source	Day	MIC Array	Identification Number
S1-D341-MB-1.	1	341	B	1
S1-D341-MB-2.	1	341	B	2
S2-D341-MB-1.	2	341	B	1
S2-D341-MB-2.	2	341	B	2
S2-D341-MB-4.	2	341	B	4
S3-D341-MB-2.	3	341	B	2
S7-D341-MB-2.	7	341	B	2

```
DAY 341:  SHOT TIME  5:36 HRS   2.024 SEC
SOURCE 1 MINE ARRAY B
MICS: 27,28,29,30,31,32      1920 VALUES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

MIC(27):  5:36 HRS  35.411 SEC       MIC(30):  5:36 HRS  39.451 SEC
MIC(28):  5:36 HRS  36.507 SEC       MIC(31):  5:36 HRS  41.499 SEC
MIC(29):  5:36 HRS  37.787 SEC       MIC(32):  5:36 HRS  43.903 SEC

THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

  MIC 1     MIC 2     MIC 3     MIC 4     MIC 5     MIC 6

   808       603       658       716       701       747

THE SIGNAL ENERGY WITHIN EACH WINDOW

   MIC 1        MIC 2        MIC 3        MIC 4        MIC 5        MIC 6

 3622710.      207322.      9752818.    26270144.    11659675.    13955643.

THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

   GAMMA(1,2)=  .558      RTAU(1,2)= -884.0      CTAU(1,2)= -.884
   GAMMA(1,3)=  .525      RTAU(1,3)=-2181.0      CTAU(1,3)=-2.182
   GAMMA(1,4)=  .471      RTAU(1,4)=-3860.0      CTAU(1,4)=-3.861
   GAMMA(1,5)=  .418      RTAU(1,5)=-5878.0      CTAU(1,5)=-5.883
   GAMMA(1,6)=  .534      RTAU(1,6)=-8218.0      CTAU(1,6)=-8.216
   GAMMA(2,3)=  .395      RTAU(2,3)=-1295.0      CTAU(2,3)=-1.297
   GAMMA(2,4)=  .412      RTAU(2,4)=-2977.0      CTAU(2,4)=-2.977
   GAMMA(2,5)=  .336      RTAU(2,5)=-4993.0      CTAU(2,5)=-4.998
   GAMMA(2,6)=  .425      RTAU(2,6)=-7334.0      CTAU(2,6)=-7.331
   GAMMA(3,4)=  .421      RTAU(3,4)=-1677.0      CTAU(3,4)=-1.679
   GAMMA(3,5)=  .370      RTAU(3,5)=-3695.0      CTAU(3,5)=-3.701
   GAMMA(3,6)=  .457      RTAU(3,6)=-6037.0      CTAU(3,6)=-6.034
   GAMMA(4,5)=  .422      RTAU(4,5)=-2017.0      CTAU(4,5)=-2.022
   GAMMA(4,6)=  .439      RTAU(4,6)=-4356.0      CTAU(4,6)=-4.355
   GAMMA(5,6)=  .376      RTAU(5,6)=-2310.0      CTAU(5,6)=-2.337

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

                         TIME(1)=   .000 SEC
                         TIME(2)=   .884 SEC
                         TIME(3)=  2.182 SEC
                         TIME(4)=  3.861 SEC
                         TIME(5)=  5.883 SEC
                         TIME(6)=  8.216 SEC

THE MET TO A BE USED AS INPUT TO POSITION ESTIMATOR

                            TEMP=  6.7 DEGS C.
                  WIND DIRECTION= 6380 MILS
                      WIND SPEED=    9 KNOTS
```

Figure 4. Results from PASS shot S1-D341-MB-1.

```
DAY 341:  SHOT TIME  8:55 HRS   1.640 SEC
SOURCE 1  MIKE ARRAY B
MICS: 27,28,29,30,31,32      1720 VALUES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

    MIC(27):  8:55 HRS  35.227 SEC        MIC(30):  8:55 HRS  39.067 SEC
    MIC(28):  8:55 HRS  36.123 SEC        MIC(31):  8:55 HRS  41.115 SEC
    MIC(29):  8:55 HRS  37.403 SEC        MIC(32):  8:55 HRS  43.419 SEC


THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

     MIC 1      MIC 2      MIC 3      MIC 4      MIC 5      MIC 6

      87[illegible]        797        860        672        894        850


THE SIGNAL ENERGY WITHIN EACH WINDOW

      MIC 1        MIC 2         MIC 3         MIC 4         MIC 5         MIC 6

     208128.       49282.      1073772.     15422260.     30297288.     18815863.


THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

      GAMMA(1,2)=   .095        RTAU(1,2)= -725.0         CTAU(1,2)= -.821
      GAMMA(1,3)=  .130         RTAU(1,3)=-2259.0         CTAU(1,3)=-2.137
      GAMMA(1,4)=  .233         RTAU(1,4)=-3916.0         CTAU(1,4)=-3.853
      GAMMA(1,5)=  .206         RTAU(1,5)=-5924.0         CTAU(1,5)=-5.860
      GAMMA(1,6)=  .197         RTAU(1,6)=-7960.0         CTAU(1,6)=-8.148
      GAMMA(2,3)=  .160         RTAU(2,3)=-1308.0         CTAU(2,3)=-1.316
      GAMMA(2,4)=  .307         RTAU(2,4)=-3034.0         CTAU(2,4)=-3.033
      GAMMA(2,5)=  .306         RTAU(2,5)=-5042.0         CTAU(2,5)=-5.040
      GAMMA(2,6)=  .271         RTAU(2,6)=-7313.0         CTAU(2,6)=-7.327
      GAMMA(3,4)=  .435         RTAU(3,4)=-1733.0         CTAU(3,4)=-1.716
      GAMMA(3,5)=  .496         RTAU(3,5)=-3740.0         CTAU(3,5)=-3.723
      GAMMA(3,6)=  .503         RTAU(3,6)=-6003.0         CTAU(3,6)=-6.011
      GAMMA(4,5)=  .835         RTAU(4,5)=-2007.0         CTAU(4,5)=-2.007
      GAMMA(4,6)=  .771         RTAU(4,6)=-4302.0         CTAU(4,6)=-4.294
      GAMMA(5,6)=  .807         RTAU(5,6)=-2295.0         CTAU(5,6)=-2.287

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

                                  TIME(1)= -5.860 SEC
                                  TIME(2)= -5.040 SEC
                                  TIME(3)= -3.723 SEC
                                  TIME(4)= -2.007 SEC
                                  TIME(5)=   .000 SEC
                                  TIME(6)=  2.287 SEC

THE MET TO A BE USED AS INPUT TO POSITION ESTIMATOR

                                        TEMP=  5.6 DEGS C.
                              WIND DIRECTION= 6380 MILS
                                  WIND SPEED=     8 KNOTS
```

Figure 5. Results from PASS shot S1-D341-MB-2.

```
    D341:  SHOT TIME 12:15 HRS     .768 SEC
    SOURCE 2 MIKE ARRAY B
    MICS: 27,28,29,30,31,32       1920 VALUES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

    MIC(27): 12:15 HRS  33.819 SEC        MIC(30): 12:15 HRS  35.227 SEC
    MIC(28): 12:15 HRS  33.819 SEC        MIC(31): 12:15 HRS  36.507 SEC
    MIC(29): 12:15 HRS  34.331 SEC        MIC(32): 12:15 HRS  38.299 SEC

THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

     MIC 1      MIC 2      MIC 3      MIC 4      MIC 5      MIC 6

      623        783        730        746        779        701

THE SIGNAL ENERGY WITHIN EACH WINDOW

      MIC 1          MIC 2          MIC 3          MIC 4          MIC 5          MIC 6

     275637.         35194.        377331.        540671.        330844.        362904.

THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

      GAMMA(1,2)    .453       RTAU(1,2)=   -14.0        CTAU(1,2)=  -.014
      GAMMA(1,3)=   .529       RTAU(1,3)=  -498.0        CTAU(1,3)=   .498
      GAMMA(1,4)=   .663       RTAU(1,4)= -1399.0        CTAU(1,4)=-1.399
      GAMMA(1,5)=   .420       RTAU(1,5)= -2708.0        CTAU(1,5)=-2.707
      GAMMA(1,6)=   .710       RTAU(1,6)= -4418.0        CTAU(1,6)=-4.418
      GAMMA(2,3)=   .441       RTAU(2,3)=  -484.0        CTAU(2,3)= -.484
      GAMMA(2,4)=   .472       RTAU(2,4)=  1384.0        CTAU(2,4) -1.385
      GAMMA(2,5)    .332       RTAU(2,5)= -2692.0        CTAU(2,5) -2.692
      GAMMA(2,6)=   .421       RTAU(2,6)= -4404.0        CTAU(2,6)=-4.403
      GAMMA(3,4)=   .581       RTAU(3,4)=  -901.0        CTAU(3,4)= -.901
      GAMMA(3,5)=   .364       RTAU(3,5)= -2206.0        CTAU(3,5)=-2.209
      GAMMA(3,6)=   .583       RTAU(3,6)= -3920.0        CTAU(3,6)=-3.920
      GAMMA(4,5)    .482       RTAU(4,5)= -1308.0        CTAU(4,5) -1.308
      GAMMA(4,6)=   .626       RTAU(4,6)= -3018.0        CTAU(4,6) -3.019
      GAMMA(5,6)=   .314       RTAU(5,6)= -1710.0        CTAU(5,6)=-1.711

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

                              TIME(1)=  -1.399 SEC
                              TIME(2)=  -1.385 SEC
                              TIME(3)=   -.901 SEC
                              TIME(4)=    .000 SEC
                              TIME(5)    1.308 SEC
                              TIME(6)    3.019 SEC

THE MET TO BE USED AS INPUT TO POSITION ESTIMATOR

                                 TEMP=  7.9 DEGS C.
                         WIND DIRECTION= 6050 MILS
                             WIND SPEED=    8 KNOTS
```

Figure 6. Results from PASS shot S2-D341-MB-1.

DAY 341: SHOT TIME 8:15 HRS 1.896 SEC
SOURCE 2 MINE ARRAY B
MICS: 27,28,29,30,31,32 1920 VALUES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

MIC(27):	8:15 HRS 34.971 SEC	MIC(30):	8:15 HRS 36.379 SEC
MIC(28):	8:15 HRS 34.971 SEC	MIC(31):	8:15 HRS 37.659 SEC
MIC(29):	8:15 HRS 35.483 SEC	MIC(32):	8:15 HRS 39.451 SEC

THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6
742	726	677	666	686	565

THE SIGNAL ENERGY WITHIN EACH WINDOW

MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6
1433169.	264966.	8322272.	21142426.	35415847.	34593879.

THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

GAMMA(1,2)= .693	RTAU(1,2)= 5.0	CTAU(1,2)= .014
GAMMA(1,3)= .703	RTAU(1,3)= -422.0	CTAU(1,3)= -.436
GAMMA(1,4)= .669	RTAU(1,4)=-1324.0	CTAU(1,4)=-1.340
GAMMA(1,5)= .653	RTAU(1,5)=-2652.0	CTAU(1,5)=-2.642
GAMMA(1,6)= .765	RTAU(1,6)=-4329.0	CTAU(1,6)=-4.319
GAMMA(2,3)= .674	RTAU(2,3)= -455.0	CTAU(2,3)= -.451
GAMMA(2,4)= .703	RTAU(2,4)=-1359.0	CTAU(2,4)=-1.354
GAMMA(2,5)= .730	RTAU(2,5)=-2656.0	CTAU(2,5)=-2.656
GAMMA(2,6)= .753	RTAU(2,6)=-4333.0	CTAU(2,6)=-4.333
GAMMA(3,4) .774	RTAU(3,4)= -903.0	CTAU(3,4)= -.903
GAMMA(3,5)= .756	RTAU(3,5)=-2201.0	CTAU(3,5)=-2.206
GAMMA(3,6)= .724	RTAU(3,6)=-3377.0	CTAU(3,6)=-3.882
GAMMA(4,5)= .795	RTAU(4,5)=-1298.0	CTAU(4,5)=-1.303
GAMMA(4,6)= .753	RTAU(4,6)=-2974.0	CTAU(4,6)=-2.979
GAMMA(5,6)= .784	RTAU(5,6)=-1676.0	CTAU(5,6)=-1.676

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

TIME(1)= -4.319 SEC
TIME(2)= -4.333 SEC
TIME(3)= -3.882 SEC
TIME(4)= -2.979 SEC
TIME(5)= -1.676 SEC
TIME(6)= .000 SEC

THE MET TO A BE USED AS INPUT TO POSITION ESTIMATOR

TEMP= 5.4 DEGS C.
WIND DIRECTION= 6180 MILS
WIND SPEED= 9 KNOTS

Figure 7. Results from PASS shot S2-D341-MB-2.

```
    DAY 341:  SHOT TIME  9:15 HRS   1.768 SEC
    SOURCE 1  MIKE ARRAY B
    MICS: 27,28,29,30,31,32       1920 VALUES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

    MIC(27):  9:15 HRS  34.843 SEC       MIC(30):  9:15 HRS  36.251 SEC
    MIC(28):  9:15 HRS  34.843 SEC       MIC(31):  9:15 HRS  37.531 SEC
    MIC(29):  9:15 HRS  35.355 SEC       MIC(32):  9:15 HRS  39.323 SEC

THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

     MIC 1     MIC 2     MIC 3     MIC 4     MIC 5     MIC 6

      856       754       762       950       804       717

THE SIGNAL ENERGY WITHIN EACH WINDOW

      MIC 1        MIC 2        MIC 3        MIC 4        MIC 5        MIC 6

     249470.       31231.      405041.     6196279.     2551576.     5881784.

THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

      GAMMA(1,2)=  .144      RTAU(1,2)=     4.0      CTAU(1,2)= -.020
      GAMMA(1,3)=  .369      RTAU(1,3)=  -414.0      CTAU(1,3)=  .416
      GAMMA(1,4)=  .410      RTAU(1,4)= -1485.0      CTAU(1,4)=-1.498
      GAMMA(1,5)=  .398      RTAU(1,5)= -2624.0      CTAU(1,5)=-2.631
      GAMMA(1,6)=  .325      RTAU(1,6)= -4394.0      CTAU(1,6)=-4.353
      GAMMA(2,3)=  .110      RTAU(2,3)=  -418.0      CTAU(2,3)= -.396
      GAMMA(2,4)=  .160      RTAU(2,4)= -1490.0      CTAU(2,4)=-1.478
      GAMMA(2,5)=  .106      RTAU(2,5)= -2510.0      CTAU(2,5)=-2.611
      GAMMA(2,6)=  .191      RTAU(2,6)= -4334.0      CTAU(2,6)=-4.333
      GAMMA(3,4)=  .322      RTAU(3,4)= -1100.0      CTAU(3,4) -1.083
      GAMMA(3,5)=  .499      RTAU(3,5)= -2208.0      CTAU(3,5)=-2.215
      GAMMA(3,6)=  .252      RTAU(3,6)= -3938.0      CTAU(3,6)=-3.33[illegible]
      GAMMA(4,5)=  .392      RTAU(4,5)= -1142.0      CTAU(4,5)=-1.132
      GAMMA(4,6)=  .444      RTAU(4,6)= -2844.0      CTAU(4,6)=-2.854
      GAMMA(5,6)=  .354      RTAU(5,6)= -1702.0      CTAU(5,6)=-1.722

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

                          TIME(1)= -2.631 SEC
                          TIME(2)= -2.611 SEC
                          TIME(3)= -2.215 SEC
                          TIME(4)= -1.132 SEC
                          TIME(5)=   .000 SEC
                          TIME(6)=  1.722 SEC

THE MET TO A BE USED AS INPUT TO POSITION ESTIMATOR

                            TEMP=  5.6 DEGS C.
                  WIND DIRECTION  6380 MILS
                      WIND SPEED=    8 KNOTS
```

Figure 8. Results from PASS shot S2-D341-MB-4.

```
DAY 341:  SHOT TIME  6: 3 HRS   1.768 SEC
SOURCE 3  MIKE ARRAY B
MICS: 27,28,29,30,31,32      1920 VALUES/MIC
```

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

```
MIC(27):  6: 3 HRS  36.251 SEC        MIC(30):  6: 3 HRS  34.843 SEC
MIC(28):  6: 3 HRS  35.355 SEC        MIC(31):  6: 3 HRS  35.355 SEC
MIC(29):  6: 3 HRS  34.843 SEC        MIC(32):  6: 3 HRS  36.251 SEC
```

THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6
799	747	824	713	709	529

THE SIGNAL ENERGY WITHIN EACH WINDOW

MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6
5933733.	300650.	4848166.	19853956.	37227458.	25859678.

THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

GAMMA(1,2)= .734	RTAU(1,2)= 908.0	CTAU(1,2)= .902
GAMMA(1,3)= .603	RTAU(1,3)= 1400.0	CTAU(1,3)= 1.401
GAMMA(1,4)= .630	RTAU(1,4)= 1423.0	CTAU(1,4)= 1.429
GAMMA(1,5)= .811	RTAU(1,5)= 1031.0	CTAU(1,5)= 1.033
GAMMA(1,6)= .606	RTAU(1,6)= 119.0	CTAU(1,6)= .115
GAMMA(2,3)= .526	RTAU(2,3)= 492.0	CTAU(2,3)= .499
GAMMA(2,4)= .552	RTAU(2,4)= 548.0	CTAU(2,4)= .526
GAMMA(2,5)= .689	RTAU(2,5)= 123.0	CTAU(2,5)= .131
GAMMA(2,6)= .488	RTAU(2,6)= -786.0	CTAU(2,6)= -.787
GAMMA(3,4)= .671	RTAU(3,4)= 22.0	CTAU(3,4)= .027
GAMMA(3,5)= .585	RTAU(3,5)= -375.0	CTAU(3,5)= -.368
GAMMA(3,6)= .532	RTAU(3,6)=-1281.0	CTAU(3,6)=-1.286
GAMMA(4,5)= .640	RTAU(4,5)= -397.0	CTAU(4,5)= -.395
GAMMA(4,6)= .536	RTAU(4,6)=-1302.0	CTAU(4,6)=-1.313
GAMMA(5,6)= .674	RTAU(5,[illegible])= -936.0	CTAU(5,6)= -.918

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

```
TIME(1)=   1.033 SEC
TIME(2)=    .131 SEC
TIME(3)=   -.368 SEC
TIME(4)=   -.395 SEC
TIME(5)=    .000 SEC
TIME(6)=    .918 SEC
```

THE MET TO A BE USED AS INPUT TO POSITION ESTIMATOR

```
          TEMP=  5.4 DEGS C.
WIND DIRECTION= 6180 MILS
    WIND SPEED=    9 KNOTS
```

Figure 9. Results from PASS shot S3-D341-MB-2.

DAY 341: SHOT TIME 6:25 HRS 1.512 SEC
SOURCE 7 MIKE ARRAY B
MICS: 27,28,29,30,31,32 1920 VALUES/MIC

THE STARTING TIMES FOR EACH MICROPHONE SIGNAL

MIC(27):	6:25 HRS	54.683 SEC	MIC(30):	6:25 HRS	50.075 SEC
MIC(28):	6:25 HRS	52.891 SEC	MIC(31):	6:25 HRS	49.051 SEC
MIC(29):	6:25 HRS	51.227 SEC	MIC(32):	6:25 HRS	48.411 SEC

THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE

MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6
841	754	375	705	731	628

THE SIGNAL ENERGY WITHIN EACH WINDOW

MIC 1	MIC 2	MIC 3	MIC 4	MIC 5	MIC 6
1766608.	306684.	6485429.	18018153.	12667278.	12637918.

THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED TIME DIFFERENCES(SEC)
BETWEEN EACH PAIR OF MICROPHONE SIGNALS

GAMMA(1,2)= .317	RTAU(1,2)= 1841.0	CTAU(1,2) 1.874
GAMMA(1,3)= .346	RTAU(1,3)= 3434.0	CTAU(1,3) 3.462
GAMMA(1,4)= .418	RTAU(1,4)= 4747.0	CTAU(1,4) 4.785
GAMMA(1,5)= .375	RTAU(1,5)= 5850.0	CTAU(1,5)= 5.803
GAMMA(1,6)= .374	RTAU(1,6)= 6547.0	CTAU(1,6) 6.498
GAMMA(2,3)= .608	RTAU(2,3)= 1593.0	CTAU(2,3) 1.588
GAMMA(2,4)= .610	RTAU(2,4)= 2909.0	CTAU(2,4)= 2.911
GAMMA(2,5)= .462	RTAU(2,5)= 3917.0	CTAU(2,5) 3.929
GAMMA(2,6)= .517	RTAU(2,6)= 4619.0	CTAU(2,6)= 4.624
GAMMA(3,4)= .558	RTAU(3,4)= 1314.0	CTAU(3,4) 1.323
GAMMA(3,5)= .505	RTAU(3,5) 2353.0	CTAU(3,5)= 2.341
GAMMA(3,6)= .435	RTAU(3,6)= 3027.0	CTAU(3,6) 3.036
GAMMA(4,5)= .542	RTAU(4,5)= 1004.0	CTAU(4,5) 1.018
GAMMA(4,6)= .503	RTAU(4,6)= 1707.0	CTAU(4,6) 1.713
GAMMA(5,6)= .581	RTAU(5,6) 699.0	CTAU(5,6)= .695

THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION ESTIMATOR

TIME(1)= 4.785 SEC
TIME(2)= 2.911 SEC
TIME(3)= 1.323 SEC
TIME(4)= .000 SEC
TIME(5)= -1.018 SEC
TIME(6)= -1.713 SEC

THE MET TO BE USED AS INPUT TO POSITION ESTIMATOR

TEMP= 5.4 DEGS C.
WIND DIRECTION= 6180 MILS
WIND SPEED= 9 KNOTS

Figure 10. Results from PASS shot S7-D341-MB-2.

Table 3. Miss Distances for PASS Data Examples

File No.	Fig. No.	Miss Distance (Meters)	Distance to Center of Array (Meters)	Ratio of Miss Distance to Total Distance
S1-D341-MB-1.	4	430.0	12,678.5	.034
S1-D341-MB-2.	5	195.5	12,678.5	.015
S2-D341-MB-1.	6	176.4	11,784.8	.015
S2-D341-MB-2	7	192.8	11,784.8	.016
S2-D341-MB-4	8	1015.2	11,784.8	.086
S3-D341-MB-2.	9	395.54	11,471.9	.034
S7-D341-MB-2.	10	291.8	16,900.7	.017

V. CONCLUSIONS

The present edition of the "Time Difference Estimator Program" has been presented in the first three sections of this report and the results from its application to a number of arbitrarily selected signals from the PASS experiment was given in the fourth section. The results show good time duration estimates, based on the concept of miss distance; however, one should realize that with only seven samples not much can be said of the programs statistical performance other than it is looking very promising.

From Table 2 and Figures 4-10 it is seen that the program satisfactorily determined relative times such that target position could be estimated with miss distances around two hundred meters for targets of about twelve kilometers in range. It appears that as one would intuitively expect, correlation coefficients much lower than 0.5 for the time differences, Figure 4 and Figure 8, result in the considerable sized miss distances given in Table 2.

The application of the program to existing data has pointed out need for further research into several areas in order to improve the procedure.

(1) In order to eliminate inaccurate data a threshold value for the correlation coefficient must be determined for which the associated time difference estimates with less than that threshold are claimed unreliable and discarded.

(2) A procedure should be developed to assign realistic weights for use in the least squares procedure perhaps as a function of the normalized correlation coefficient.

(3) The overall effectiveness of the procedure should be established by providing the variance or a bound on the variances of the time

difference estimates. This will require a theoretical development along with an examination of a large amount of data for experimental verification.

(4) The program should be altered to present a workable procedure for handling the multiple target problem.

APPENDIX A

Time Differences Estimator Program Listing

```
C
C                    TIME DIFFERENCES ESTIMATOR PROGRAM
C
C   GENERAL DESCRIPTION: THIS PROGRAM WILL ACCEPT A GIVEN NUMBER
C         OF MICROPHONE SIGNALS EACH CONTAINING A SPECIFIED NUMBER
C         OF DATA POINTS FROM A FIXED DATA FORMAT AND DETERMINE THE TIME
C         DIFFERENCES BETWEEN SIGNAL BURSTS THAT APPEAR WITHIN THE
C         RECORD LENGTH.
C
C
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C
C
C
C   GLOSSARY OF VARIABLES:
C
C         NMIC- NUMBER OF MICROPHONES
C           NL= NUMBER OF DATA POINTS FOR EACH MICROPHONE
C          NSW= NUMBER OF POINTS IN SLIDING WINDOW
C         NFFW= NUMBER OF POINTS IN THE FOURIER WINDOW
C    SMIC(J,I)= SIGNAL AMPLITUDE FOR MIC J AT TIME I RELATIVE TO IT(J)
C        IT(J)= STARTING TIME FOR MICROPHONE J IN MSEC RELATIVE TO BEG.
C      LRST(J)= ROUGH STARTING POINT FOR MICROPHONE J RELATIVE TO IT(J)
C        NR(I)= START TIME FOR FOURIER WINDOW OF MIC I RELATIVE TO IT(I)
C         E(J)= ENERGY WITHIN CORRELATION WINDOW FOR SIGNAL J
C    TAU(I,J)= RAW TIME DIFFERENCE BETWEEN WINDOWED SIGNALS J AND I
C   RTAU(I,J)= ROUGH TIME DIFFERENCE BETWEEN MICROPHONES I AND J
C               DETERMINED BY CORRELATION
C    CTAU(I,J)  IMPROVED TIME DIFFERENCE BETWEEN MICROPHONE I AND J BY
C               LEAST SQUARED ERROR FIT(RELATIVE)
C    GAM(I,J)= NORMALIZED CORRELATION COEF BETWEEN MIC J AND I SIGNALS
C      G(I,J)= RELIABILITY WEIGHT ASSIGNED TO RTAU(I,J) FOR THE
C               LEAST SQUARE PROCEDURE
C       AT(J)   TIME DIFFERENCE OF SIGNAL J RELATIVE TO MIC 1 SIGNAL
C     TIME(I)   RELATIVE TIME OF THE I TH SIGNAL FOR POSITION ESTIMATOR
C      A(J,I)- AUGMENTED COEFFICIENT MATRIX FOR LEAST SQUARE FIT
C       IC(I)- CONTROL VARIABLES FOR SUBROUTINE GJR
C        V(I)- VARIABLES V(1) AND V(2) FOR INPUT TO GJR SUBROUTINE
C    CMEAS(I)- OVERALL MEASURE OF CORRELATION FOR MIC 1
C    IFOMB(I)= STARTING AND STOPPING FREQUENCY VALUES FOR 60 HZ
C               COMB AND LOW PASS FILTER
C        X(I)- I TH VALUE OF FIRST SIGNAL FOR CROSS CORRELATION- INPUT
C               I TH VALUE OF FOURIER TRANSFORM ON OUTPUT
C        Y(I)   I TH VALUE OF SECOND SIGNAL FOR CROSS CORRELATION  INPUT
C               I TH VALUE OF FOURIER TRANSFORM ON OUTPUT
C     WORK(I)- WORK SPACE SPECIFIED BY FOURG SUBROUTINE
C       XX(I)   I TH VALUE OF ESTIMATE OF NOISE ENERGY SPECTRUM
C       YY(I)   I TH VALUE OF ESTIMATE OF SIGNAL PLUS NOISE SPECTRUM
C       ZZ(I)- VALUE OF PREFILTER AT THE I TH FREQUENCY
C     IDAY(I)- DAY OF THE START OF THE I TH MICROPHONE SIGNAL
C    IHOUR(I)   HOUR OF THE START OF THE I TH MICROPHONE SIGNAL
C     IMIN(I)   MINUTE OF THE START OF THE ITH MICROPHONE SIGNAL
C      SEC(I)= SECOND OF THE START OF THE I TH MICROPHONE SIGNAL
C      MIC(I)= PASS MICROPHONE NUMBER ASSOCIATED WITH MICROPHONE I
C
```

```
C     INITIALIZING
C
      DIMENSION IDAY(6),IHOUR(6),IMIN(6),SEC(6),MIC(6),TIME(6)
      DIMENSION TAU(6,6),IT(6),NR(6),F(6),RTAU(6,6),CTAU(6,6),GAG(6,6)
      DIMENSION SMIC(6,1920),LRST(6),G(6,6),AT(6),A(5,6),JC(5),V(2)
      DIMENSION CMEAS(6),MCOMB(11)
      COMPLEX X(1024),Y(1024),WORK(1024),XX(1024),YY(1024),ZZ(1024)
      NMIC=6
      NL=1920
      NSW=342
      NPFW=512
C
C  BRINGING IN DATA FROM MASTER FILE
C
      CALL RDATA(SMIC,MIC,IDAY,IHOUR,IMIN,SEC,TEMP,MILS,KNOTS)
      DO 50 I=1,NMIC
      ISEC=SEC(I)*1000
      IT(I)=IHOUR(I)*60*60*1000+IMIN*60*1000+ISEC
   50 CONTINUE
C
C COMPUTATION OF ROUGH ARRIVAL TIMES
C
      DO 100 J=1,NMIC
      TE=0.0
      EMAX=0.0
      LMAX=0
      DO 90 K=1,NSW
      C=SMIC(J,K)*SMIC(J,K)
      TE=TE+C
   90 CONTINUE
      EMAX=TE
      LMAX=0
      NLP=NL-NSW
      DO 95 K=1,NLP
      TE =TE+SMIC(J,NSW+K)*SMIC(J,NSW+K)- SMIC(J,K)*SMIC(J,K)
      IF(TE.LT.EMAX) GO TO 95
      EMAX=TE
      LMAX=K
   95 CONTINUE
      LRST(J)=LMAX
  100 CONTINUE
C
C  COMPUTATION OF WINDOW STARTING POINTS
C
      DO 110 I=1,NMIC
      INSW=NSW/4
      MRST=LRST(I)-INSW
      IF(MRST.GT.0) GO TO 105
      NR(I)=0
      GO TO 110
  105 CONTINUE
      NP=NL-NPFW
      IF(MRST.LT.NP) GO TO 106
      NR(I)=NP
      IT(I)=IT(I)+NP
      GO TO 110
  106 NR(I)=LRST(I)-INSW
      IT(I)=IT(I)+NR(I)
  110 CONTINUE
C
```

```
C  PRINTING THE WINDOW STARTING TIMES
C
      WRITE(6,2011)
 2011 FORMAT(//' THE WINDOW STARTING TIMES(MSEC) RELATIVE TO ABOVE '/)
      WRITE(6,2013)
 2013 FORMAT('        MIC 1      MIC 2      MIC 3      MIC 4      MIC 5      M
     .IC 6'/)
      WRITE(6,2010)NR
 2010 FORMAT(1X,6(I10))
C
C COMPUTATION OF SIGNAL ENERGY WITHIN FOURIER WINDOW
C
      DO 115 J=1,NMIC
      SUM=0.0
      KSTAR=NR(J)+1
      KSTOP=NR(J)+NPFW
      DO 112 K=KSTAR,KSTOP
      P=SMIC(J,K)*SMIC(J,K)
      SUM=SUM+P
  112 CONTINUE
  115 E(J)=SUM
C
C  PRINTING THE SIGNAL ENERGY WITHIN EACH WINDOW
C
      WRITE(6,2007)
 2007 FORMAT(//' THE SIGNAL ENERGY WITHIN EACH WINDOW'/)
      WRITE(6,2014)
 2014 FORMAT('        MIC 1         MIC 2         MIC 3         MIC 4
     .   MIC 5        MIC 6'/)
      WRITE(6,2008)E
 2008 FORMAT(6(F13.0))
C
C  POSITIONING OF SIGNALS FOR DETERMINING THE CROSS CORRELATION
C
      DO 200 I=1,5
      KT=I+1
      DO 150 J=KT,NMIC
      KA=NR(I)
      DO 120 L=1,512
      KAL=KA+L
      SM=SMIC(I,KAL)
      X(L)=CMPLX(SM,0.0)
      Y(L)=CMPLX(0.0,0.0)
  120 CONTINUE
      DO 130 L=513,1024
      X(L)=CMPLX(0.0,0.0)
      KB=NR(J)
      KALP=KB+L-512
      SKAL=SMIC(J,KALP)
      Y(L)=CMPLX(SKAL,0.0)
  130 CONTINUE
      CALL FOURG(X,1024,-1,WORK)
      CALL FOURG(Y,1024,-1,WORK)
C
C  DETERMINATION OF STATING POINT FOR NOISE WINDOW
C
      KXX=NR(I)-513
      KYY=NR(J)-513
      DO 125 L=1,512
      LI=L+512
```

```
      XX(LI)=CMPLX(0.0,0.0)
      YY(LI)=CMPLX(0.0,0.0)
      IF(KXX.LT.1)GO TO 116
      MXX=KXX+L
      SXX=SMIC(I,MXX)
      XX(L)=CMPLX(SXX,0.0)
  118 CONTINUE
      IF(KYY.LT.1)GO TO 117
      MYY=KYY+L
      SYY=SMIC(J,MYY)
      YY(L)=CMPLX(SYY,0.0)
      GO TO 125
  116 XX(L)=CMPLX(0.0,0.0)
      GO TO 118
  117 YY(L)=CMPLX(0.0,0.0)
  125 CONTINUE
C
C  DETERMINATION OF ESTIMATE OF NOISE SPECTRUM
C
      CALL FOURG(XX,1024,-1,WORK)
      CALL FOURG(YY,1024,-1,WORK)
      DO 135 L=1,1024
      ZZ(L)=CONJG(XX(L))
      XX(L)=XX(L)*ZZ(L)
      ZZ(L)=CONJG(YY(L))
      YY(L)=YY(L)*ZZ(L)
      YY(L)=(XX(L)+ZZ(L))/2.
C
C  DETERMINATION OF ESTIMATE OF SIGNAL PLUS NOISE SPECTRUM
C
      ZZ(L)=Y(L)
      Y(L)=CONJG(Y(L))
      XX(L)=Y(L)*ZZ(L)
      ZZ(L)=CONJG(X(L))
      ZZ(L)=ZZ(L)*X(L)
      XX(L)=(XX(L)+ZZ(L))/2.
C
C   COMPUTATION OF PREFILTER VALUES
C
      PRA=REAL(XX(L))
      PRB=REAL(YY(L))
      PRD=.001
      IF(PRA.GT.PRD)GO TO 716
      PREF=1.0
      GO TO 721
  716 CONTINUE
      PRC=PRB/PRA
      IF(PRC.GT.1.)GO TO 719
      PREF=1.0-PRC
      GO TO 721
  719 PREF=0.0
  721 CONTINUE
      ZZ(L)=CMPLX(PREF,PREF)
      Y(L)=X(L)*Y(L)
      Y(L)=Y(L)/1024.
C
C  APPLICATION OF PREFILTER
C
      Y(L)=Y(L)*ZZ(L)
C
```

```
C  APPLICATION OF COMB FILTER FOR 60 CYCLE AND HARMONICS
C
  135 CONTINUE
      DATA MCOMB/1,2,10,60,65,121,126,183,188,244,249/
      NX=MCOMB(1)
      IF(NX.LE.0) GO TO 131
      Y(1)=CMPLX(0.0,0.0)
  131 DO 133 N=2,10,2
      NX=MCOMB(N)
      IF(NX.LE.0) GO TO 138
      NY=MCOMB(N+1)
      DO 132 LL=NX,NY
      Y(LL)=CMPLX(0.0,0.0)
      MX=2*NPFW+2-LL
      Y(MX)=CMPLX(0.0,0.0)
  132 CONTINUE
  133 CONTINUE
  138 CONTINUE
C
C  FINDING THE RAW TIME DIFFERENCES BETWEEN THE WINDOWED SIGNALS
C
      CALL FOURG(Y,1024,+1,WORK)
      CMAX=0.
      TMAX=0.
      DO 140 L=1,1024
      CA=REAL(Y(L))
      CA=ABS(CA)
      IF(CA.LE.CMAX) GO TO 140
      CMAX=CA
      TMAX=L
  140 CONTINUE
      TAU(I,J)=TMAX-NPFW-1
C
C  DETERMINATION OF THE NORMALIZED CORRELATION COEFFICIENT
C
      G(I,J)=CMAX/((E(J)*E(I))**0.5)
      GAM(I,J)=G(I,J)
  150 CONTINUE
  200 CONTINUE
C
C  DETERMINATION OF ROUGH TIME DIFFERENCES BETWEEN SIGNALS I AND L
C
      WRITE(6,2016)
      WRITE(6,2017)
 2017 FORMAT(' BETWEEN EACH PAIR OF MICROPHONE SIGNALS'/)
      DO 250 I=1,5
      KX=I+1
      DO 240 L=KX,NMIC
      RTAU(I,L)=FLOAT(IT(1)-IT(L))+TAU(I,L)
 2016 FORMAT(//' THE CORRELATION, TIME DIFFERENCES(MSEC), AND CORRECTED
     .TIME DIFFERENCES(SEC) ')
  240 CONTINUE
  250 CONTINUE
C
C  SELECTION OF MIC TO BE USED AS REFERENCE
C
      CMEAS(1)=G(1,2)+G(1,3)+G(1,4)+G(1,5)+G(1,6)
      CMEAS(2)=G(1,2)+G(2,3)+G(2,4)+G(2,5)+G(2,6)
      CMEAS(3)=G(1,3)+G(2,3)+G(3,4)+G(3,5)+G(3,6)
      CMEAS(4)=G(1,4)+G(2,4)+G(3,4)+G(4,5)+G(4,6)
```

```
      CMEAS(5)=G(1,5)+G(2,5)+G(3,5)+G(4,5)+G(5,6)
      CMEAS(6)=G(1,6)+G(2,6)+G(3,6)+G(4,6)+G(5,6)
      CC=0.0
      DO 255 I=1,6
      IF(CMEAS(I).LT.CC) GO TO 255
      CC=CMEAS(I)
      K=I
      KMAX=K
  255 CONTINUE
C
C  ESTABLISHMENT OF WEIGHTS FOR LEAST SQUARE TIME FIT
C
      DO 275 I=1,5
      KU=I+1
      DO 270 J=KU,6
      IF(G(I,J).LT.0.5) GO TO 266
  265 G(I,J)=GAM(I,J)**0.5
      GO TO 270
  266 G(I,J)=GAM(I,J)*GAM(I,J)
  270 CONTINUE
  275 CONTINUE
C
C  DETERMINATION OF LEAST SQUARES TIME FIT WITH MIC(1) AS REFERENCE
C
      DO 290 I=1,4
      KX=I+1
      DO 280 J=KX,5
      A(I,J)=-G(I+1,J+1)
      A(J,I)=A(I,J)
  280 CONTINUE
  290 CONTINUE
      A(1,1)=G(1,2)+G(2,3)+G(2,4)+G(2,5)+G(2,6)
      A(2,2)=G(1,3)+G(2,3)+G(3,4)+G(3,5)+G(3,6)
      A(3,3)=G(1,4)+G(2,4)+G(3,4)+G(4,5)+G(4,6)
      A(4,4)=G(1,5)+G(2,5)+G(3,5)+G(4,5)+G(5,6)
      A(5,5)=G(1,6)+G(2,6)+G(3,6)+G(4,6)+G(5,6)
      AA=-G(1,2)*TAU(1,2)+G(2,3)*TAU(2,3)+G(2,4)*TAU(2,4)
      A(1,6)=AA+G(2,5)*TAU(2,5)+G(2,6)*TAU(2,6)
      BB=-G(1,3)*TAU(1,3)-G(2,3)*TAU(2,3)+G(3,5)*TAU(3,5)
      A(2,6)=BB+G(3,4)*TAU(3,4)+G(3,6)*TAU(3,6)
      CC=-G(1,4)*TAU(1,4)-G(2,4)*TAU(2,4)-G(3,4)*TAU(3,4)
      A(3,6)=CC+G(4,5)*TAU(4,5)+G(4,6)*TAU(4,6)
      DD=-G(1,5)*TAU(1,5)-G(2,5)*TAU(2,5)-G(3,5)*TAU(3,5)
      A(4,6)=DD-G(4,5)*TAU(4,5)+G(5,6)*TAU(5,6)
      EE=-G(1,6)*TAU(1,6)-G(2,6)*TAU(2,6)-G(3,6)*TAU(3,6)
      A(5,6)=EE-G(4,6)*TAU(4,6)-G(5,6)*TAU(5,6)
      V(1)=4
      CALL GJR(A,6,5,5,6,$400,JC,V)
      AT(1)=0.
      DO 295 K=2,6
      AT(K)=A(K-1,6)
  295 CONTINUE
C
C  ADJUSTMENT OF TIME DIFFERENCES
C
      DO 310 I=1,5
      KT=I+1
      DO 300 J=KT,6
      TAU(I,J)=AT(I)-AT(J)
      CTAU(I,J)=TAU(I,J)+FLOAT(IT(I)-IT(J))
```

```
      CTAU(I,J)=CTAU(I,J)/1000.
C
C  PRINTING CORRELATION COEF AND ROUGH AND CORRECTED TIME DIFFERENCES
C
      WRITE(6,2001)I,J,GAM(I,J),I,J,RTAU(I,J),I,J,CTAU(I,J)
 2001 FORMAT(6X,' GAMMA('I1,',''I1,')='F6.3,7X,'RTAU('I1,',''I1,')='F7.1,/
     .X,'CTAU('I1,',''I1,')='F6.3)
  300 CONTINUE
  310 CONTINUE
C
C   DETERMINATION OF RELATIVE TIMES FOR THE POSITION ESTIMATOR
C
      DO 620 I=1,5
      KX=I+1
      DO 610 L=KX,NMIC
      CTAU(L,I)=-CTAU(I,L)
  610 CONTINUE
  620 CONTINUE
      DO 640 J=1,6
      IF(J.NE.KMAX)GO TO 630
      TIME(J)=0.00
      GO TO 640
  630 CONTINUE
      TIME(J)=CTAU(J,KMAX)
  640 CONTINUE
C
C  PRINTING THE RELATIVE TIMES FOR POSITION ESTIMATOR
C
      WRITE(6,2005)
 2005 FORMAT(//' THE TIMES IN SEC TO BE USED FOR INPUT TO A POSITION EST
     .IMATOR'/)
      DO 503 I=1,NMIC
      WRITE(6,2003)I,TIME(I)
 2003 FORMAT(30X,'TIME('I1,')='F7.3,' SEC')
  503 CONTINUE
      WRITE(6,2025)
 2025 FORMAT(/)
C
C  OUTPUTTING THE MET INFORMATION
C
      WRITE(6,2021)
 2021 FORMAT(' THE MET TO A BE USED AS INPUT TO POSITION ESTIMATOR'/)
      WRITE(6,2022)TEMP
 2022 FORMAT(32X,' TEMP= 'F4.1,' DEGS C.')
      WRITE(6,2023)MILS
 2023 FORMAT(22X,' WIND DIRECTION= 'I4,' MILS')
      WRITE(6,2024)KNOTS
 2024 FORMAT(26X,' WIND SPEED= 'I4,' KNOTS')
      GO TO 401
  400 WRITE(6,2015)
 2015 FORMAT(30H AN OVERFLOW HAS BEEN DETECTED )
  401 CONTINUE
      STOP
      END
```

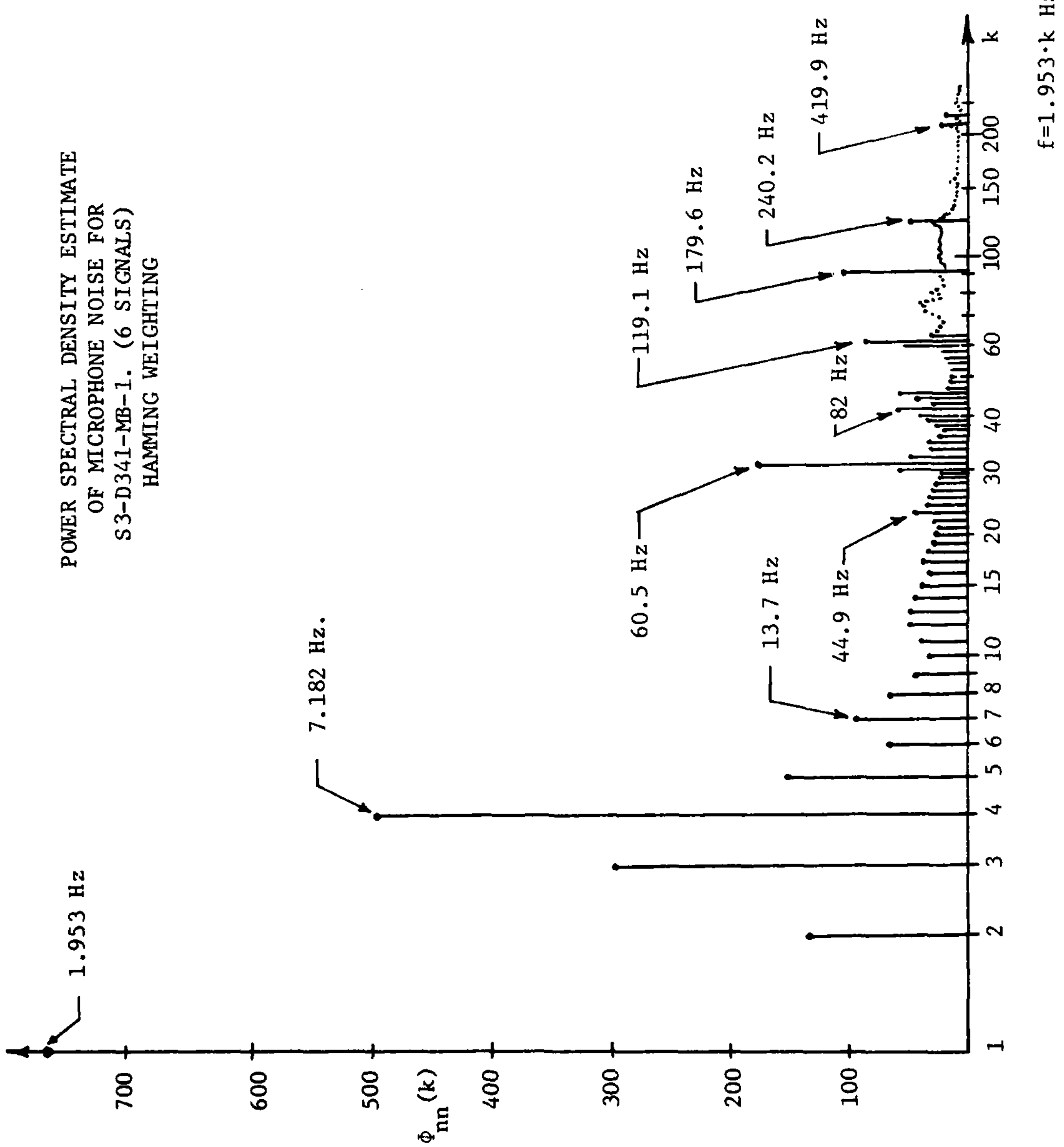
APPENDIX B

Subroutine RDATA Program Listing

```
C
C                        SUBROUTINE RDATA
C
      SUBROUTINE RDATA(SMIC,MI ,IDAY,IHOUR,IMIN,SEC,TEMP,MILS,KNOTS)
      DIMENSION MIC(6),IDAY(6),IHOUR(6),IMIN(6),SEC(6),SMIC(6,1920)
      INTEGER VALUES(6),VAL
      READ(12,111)MIKTOT,MSORC,MD,MH,MMIN,SSEC,TEMP,MILS,KNOTS
  111 FORMAT(I3,I3,1X,I3,1X,I2,1X,I2,1X,F6.3,3X,F4.1,1X,I4,1X,I2)
      MH=MH-7
      WRITE(6,115)
  115 FORMAT(///)
      WRITE(6,112)MD,MH,MMIN,SSEC
  112 FORMAT(4X,' DAY 'I3,':  SHOT TIME 'I2,':'I2,' HRS  'F6.3,' SEC')
      READ(12,221)
  221 FORMAT(5X,50H                                                  )
      WRITE(6,221)
      DO 11 I=1,MIKTOT
      READ(12,333) VALUES(I),MIC(I),IDAY(I),IHOUR(I),IMIN(I),SEC(I)
      IHOUR(I)=IHOUR(I)-7
  333 FORMAT(3X,I6,5X,I3,I4,I3,I3,F7.3)
   11 CONTINUE
      WRITE(6,225)MIC(1),MIC(2),MIC(3),MIC(4),MIC(5),MIC(6),VALUES(1)
  225 FORMAT(4X,' MICS: 'I2,',',I2,',',I2,',',I2,',',I2,',',I2,3X,I6,' VALUES
     ./MIC')
      WRITE(6,227)
  227 FORMAT(/' THE STARTING TIMES FOR EACH MICROPHONE SIGNAL'/)
      DO 25 I=1,3
      J=I+3
      WRITE(6,229)MIC(I),IHOUR(I),IMIN(I),SEC(I),MIC(J),IHOUR(J),
     .IMIN(J),SEC(J)
  229 FORMAT(4X,' MIC('I2,'): 'I2,':'I2,' HRS  'F6.3,' SEC'5X,'  MIC('I2
     .,'): 'I2,':'I2,' HRS  'F6.3,' SEC')
   25 CONTINUE
      DO 22 I=1,MIKTOT
      VAL=VALUES(I)
      READ(12,444) (SMIC(I,J),J=1,VAL)
   22 CONTINUE
  444 FORMAT(16F5.0)
      RETURN
      END
```

APPENDIX C

An Estimate of the Noise Power Spectral Density for a PASS Run



APPENDIX D

Derivation of Weighted Least Square Solution

The performance index to be minimized is given by

$$e = \sum_{i>j}^{N} \sum_{j=1}^{N} \gamma_{ij}[\tau_{ij}-(t_i-t_j)]^2$$

In this expression τ_{ij} represents the estimate of the rough time difference between signals from microphone i and j, γ_{ij} is the weight associated with that estimate, and t_i is the time of arrival of the signal at microphone i. If we select $t_1 = 0$ as a reference and use six microphones, e can be written as follows.

$$e = \gamma_{12}(\tau_{12}-(-t_2))^2 + \gamma_{13}(\tau_{13}-(-t_3))^2 + \cdots + \gamma_{16}(\tau_{16}-(-t_6))^2$$

$$+ \sum_{i>j}^{6} \sum_{j=2}^{6} \gamma_{ij}[\tau_{ij}-(t_i-t_j)]^2$$

A necessary, in this case sufficient because of convexity, condition for e to be minimized is that

$$\frac{\partial e}{\partial t_i} = 0 \qquad i = 2,3,\ldots,6$$

Taking the partial derivitives of e we have the following set of simultaneous linear equations in t_2, t_3,...,t_6 that can be easily solved.

$$\begin{bmatrix} \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} = - \begin{bmatrix} \gamma_{22} & \gamma_{23} & \gamma_{24} & \gamma_{25} & \gamma_{26} \\ \gamma_{23} & \gamma_{33} & \gamma_{34} & \gamma_{35} & \gamma_{36} \\ \gamma_{24} & \gamma_{34} & \gamma_{44} & \gamma_{45} & \gamma_{46} \\ \gamma_{25} & \gamma_{35} & \gamma_{45} & \gamma_{55} & \gamma_{56} \\ \gamma_{26} & \gamma_{36} & \gamma_{46} & \gamma_{56} & \gamma_{66} \end{bmatrix} \begin{bmatrix} t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \end{bmatrix}$$

where

$$\alpha_2 = -\gamma_{12}T_{12} + \gamma_{23}T_{23} + \gamma_{24}T_{24} + \gamma_{25}T_{25} + \gamma_{26}T_{26}$$

$$\alpha_3 = -\gamma_{13}T_{13} - \gamma_{23}T_{23} + \gamma_{34}T_{34} + \gamma_{35}T_{35} + \gamma_{36}T_{36}$$

$$\alpha_4 = -\gamma_{14}T_{14} - \gamma_{24}T_{24} - \gamma_{34}T_{34} + \gamma_{45}T_{45} + \gamma_{46}T_{46}$$

$$\alpha_5 = -\gamma_{15}T_{15} - \gamma_{25}T_{25} - \gamma_{35}T_{35} - \gamma_{45}T_{45} + \gamma_{56}T_{56}$$

$$\alpha_6 = -\gamma_{16}T_{16} - \gamma_{26}T_{26} - \gamma_{36}T_{36} - \gamma_{46}T_{46} - \gamma_{56}T_{56}$$

and

$$\gamma_{22} = -(\gamma_{12} + \gamma_{23} + \gamma_{24} + \gamma_{25} + \gamma_{26})$$

$$\gamma_{33} = -(\gamma_{13} + \gamma_{23} + \gamma_{34} + \gamma_{35} + \gamma_{36})$$

$$\gamma_{44} = -(\gamma_{14} + \gamma_{24} + \gamma_{34} + \gamma_{45} + \gamma_{46})$$

$$\gamma_{55} = -(\gamma_{15} + \gamma_{25} + \gamma_{35} + \gamma_{45} + \gamma_{56})$$

$$\gamma_{66} = -(\gamma_{16} + \gamma_{26} + \gamma_{36} + \gamma_{46} + \gamma_{56})$$

In the present edition of the program this set of equations was solved by using a canned subroutine. If computer storage becomes a problem the solution vector can be obtained by using a form of the steepest descent algorithm.

GLOSSARY OF PROGRAM VARIABLES

NMIC = Number of Microphones

NL = Number of data points for each microphone

NSW = Number of points in the sliding window

NPFW = Number of points in the Fourier window

SMIC(J,I) = Signal amplitude for MIC J at time I relative to IT(J)

IT(I) = Starting time for microphone I in MSEC relative to blast

LRST(I) = Rough starting point for microphone I relative to IT(I)

NR(I) = Starting time (MSEC) for Fourier window for microphone signal I relative to IT(I)

E(I) = Energy within correlation window for signal I

TAU(J,I) = Raw time difference between windowed signals J and I

RTAU(J,I) = Rough time difference between signal from microphones J and I determined by correlation

CTAU(J,I) = Corrected time difference between microphone J and I by least squared error fit

GAM(J,I) = Normalized correlation coef between signals from microphones J and I

G(J,I) = Reliability weight assigned to RTAU(J,I) for the least square procedure

AT(I) = Time difference shift of signal I relative to MIC 1 signal

TIME(I) = Relative time of the Ith signal for position estimator

A(J,I) = Augmented coefficient matrix for least square fit

JC(I) = Control variable for Subroutine GJR

V(I) = Variables V(1) and V(2) for input to linear equation solution subroutine GJR

CMEAS(I) = Overall measure of correlation for microphone I

X(I) = Ith value of first signal for cross correlation on input

Ith value of Fourier transfer on output

Y(I) = Ith value of second signal for cross correlation on input

Ith value of Fourier tranform on output

WORK(I) = Work space specified by FOURG subroutine

XX(I) = Ith value of estimate of noise spectrum

YY(I) = Ith value of estimate of signal plus noise spectrum

ZZ(I) = Value at Ith freq for prefilter

IDAY(I) = Day of the start of the Ith microphone signal

IHOUR(I) = Hour of the start of the Ith microphone signal

IMIN(I) = Min of the start of the Ith microphone signal

SEC(I) = Sec of the start of the Ith microphone signal

MIC(I) = PASS microphone number associated with mic I

KMAX = Microphone number selected for reference

TEMP = Effective temperature at time of shot in Deg. C.

MILS = The effective wind direction at time of shot in mils

KNOTS = The effective wind speed at time of shot in knots

KXX = Noise window starting point for SMIC(I,L)

KYY = Noise window starting point for SMIC(J,L)

PREF = Real and imaginary value of prefilter

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